Low noise position sensitive detector for optical probe beam deflection measurements

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We report the design of an optical position sensor that uses two discrete photodiodes electrically connected in parallel, with opposing polarities. A lens provides optical gain and restricts the acceptance angle of the detector. The response of the device to displacements of an optical spot is similar to that of a conventional bicell type position sensitive detector. However, the discrete photodiode design enables simpler electronic amplification with inherently less electrical noise than the bicell. Measurements by the sensor of the pointing noise of a focused helium–neon laser as a function of frequency demonstrate high sensitivity and suitability for optical probe beam deflection experiments. [S0034-6748(96)03507-1]

I. INTRODUCTION

A solid state position sensitive detector can be used for monitoring the location of an optical spot that is incident upon the active surface of the device.[1] For measuring displacements in one dimension, two types of monolithic photodetectors are commercially available. The lateral effect[2] detector incorporates an electrically resistive layer over the active surface area of a single photodiode, with electrical contacts at either end of the layer. This type of detector is useful for measuring the centroid of an optical spot that may move across the entire photosensitive area. The other type, called the bicell, is sensitive to displacements that are small compared to the size of the optical spot, and commonly is used to monitor perturbations of a probe beam caused by mechanical vibration or optical misalignment. The bicell sensitivity is sufficient for use in atomic force microscopy,[3] in which an optical beam is reflected off of the back surface of a small contact probe that is scanned across a solid sample surface. By monitoring the deflection of the beam, it is possible to generate surface topography images with atomic resolution. Position sensitive detectors also are used for observing the ''mirage effect,'' upon which photothermal deflection spectroscopy[4–6] is based. In photothermal deflection spectroscopy, a sample absorbs excitation radiation, producing thermal gradients in or adjacent to the sample. Refractive index gradients accompany the thermal gradients, causing the deflection of an optical probe beam, which is monitored as a measure of radiative absorption. The position sensitive detector reported in this work has been developed specifically for increasing the capability of optical probe beam deflection measurements.

II. THEORY

The bicell consists of two photodiode segments manufactured from a single piece of doped semiconductor material. Like the lateral detector, the bicell uses three electrical leads. One lead is common to both sides of the detector, and the other two provide separate paths for the photocurrent, allowing for discrimination based on position. Both designs require for electronic amplification[7,8] two op-amps, with feedback resistors $R(\Omega)$ for converting the currents produced by the photodiode segments into measurable voltages. Figure 1 shows the basic circuit for these commercially available sensors. The difference between the op-amp output voltages, (V_2-V_1), is taken as a measure of the deflection signal. It is possible also to use the sum of the two op-amp output voltages, (V_1+V_2), as a measurement of optical power, for normalization purposes. Under optimal design conditions, the dominant source of electrical output noise, $V_n(V)$, for each op-amp in the circuit is the thermal (Johnson) noise,[9] which originates from the feedback resistors:

$$V_n=\sqrt{4kTBR}, \tag{1}$$

where k is Boltzmann's constant $(1.38\times10^{-23}$ J/K), T is the temperature (K), B is the noise bandwidth (Hz), and R is the feedback resistance (Ω). In this type of current-to-voltage amplifier, the value of the feedback resistor R is equal to the gain of the circuit in units of volts per ampere. Therefore, the effective current measurement noise, $i_n(A)$, is inversely proportional to the square root of the gain:

$$i_n=\sqrt{4kTB/R}. \tag{2}$$

Equation (2) implies that maximizing the value of the feedback resistors reduces electrical noise in a measurement of photocurrents. However, a practical limitation on increasing the value of R is that the output of each op-amp can become saturated. For example, if a conventional position sensitive detector is used to monitor a 2 mW helium–neon laser ($\lambda=633$ nm), and the sensitivity of the detector at this wavelength is 0.33 A/W (typical for silicon photodiodes), then the photocurrent input to each op-amp is equal to 0.33

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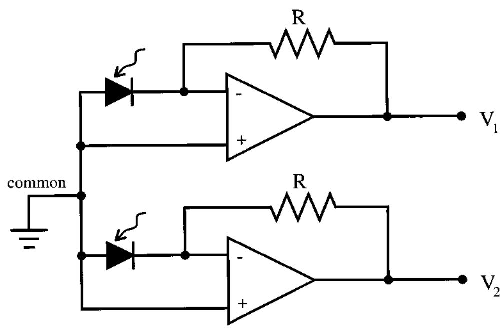

FIG. 1. Schematic diagram for electronic amplification of a conventional bicell detector. The difference between the op-amp voltages, (V_2-V_1), is taken as a measure of the deflection signal.

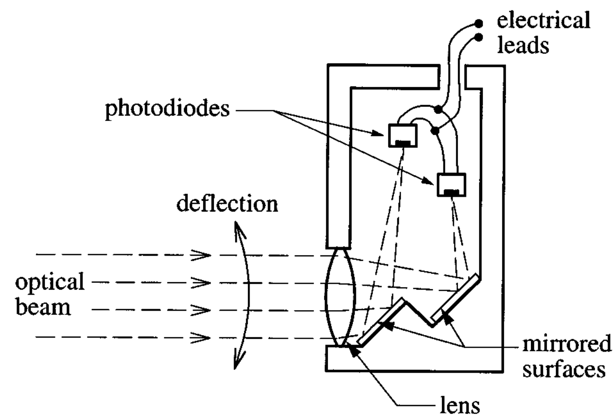

FIG. 3. Sketch of discrete photodiode position sensor design.

mA. An op-amp might specify a maximum output voltage of 10 V, which would limit the gain of each op-amp circuit to no more than 3×10^4 V/A.

Unlike a conventional position sensitive detector, our design uses two discrete photodiodes that are electronically connected in parallel, with opposing polarities. As Fig. 2 illustrates, this arrangement allows one op-amp to be used rather than two. When the beam is incident upon the center of the detector, the photocurrents produced in the two detectors are equal, and the current input to the op-amp is null. Therefore, to reduce the effect of thermal noise, the feedback resistor can be increased to an arbitrarily large value, and op-amp saturation will not occur. This feature of the discrete photodiode detector enables an improvement in signal-to-noise ratio.

III. EXPERIMENT

The probe beam must be separated into two parts by optical means, and directed to the photodiodes. As Fig. 3 shows, we achieved this by using two mirrors, one with a well-defined straight edge. This edge sharply divides the optical beam, performing the same function as the border between two segments of a conventional bicell. A lens (focal length=35 mm) focuses the portions of the beam onto the photodiodes (Hamamatsu model S2386-18K, surface area $=1.2$ mm^2), intensifying the incident radiation, and restricting the amount of unwanted stray light that reaches the diodes. Noise characteristics were tested by connecting the device directly to the current input channel (gain$=10^6$ V/A) of a Stanford Research Systems Model 830 Lock-in Amplifier. This lock-in amplifier is equipped with an internal algorithm that measures noise as a function of frequency using a mean average deviation (MAD) method. Three conditions were used to measure noise with the detector.

First, the photodiodes of the sensor were placed in a dark environment and the current noise was observed by scanning the reference frequency from 10 to 100 Hz and recording data at 2 Hz intervals. This limited frequency range was chosen because of its usefulness in photothermal deflection spectroscopy. The purpose of the initial test was to determine the internal electrical noise of the amplification system, and also to check for other contributions to electrical noise, such as capacitive and inductive coupling, and microphonic noise. The low-pass filter of the lock-in amp was set with a time constant of 100 ms and a 12 dB/octave rolloff, for an effective noise bandwidth of 1.25 Hz. The rms noise, as shown by Fig. 4, is on the order of 0.5 pA/$\sqrt{\text{Hz}}$, which originates primarily from the current preamplifier within the lock-in amplifier.

Next, the detector was used for observing the pointing stability of a focused Uniphase Model 1303P helium–neon

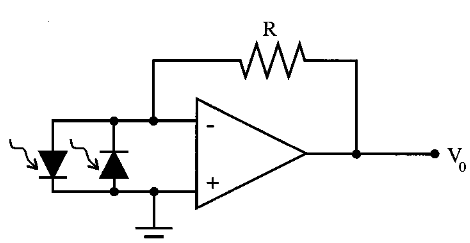

FIG. 2. Diagram for amplification of a discrete photodiode position sensor. The output voltage, V_0, is taken as a measure of deflection.

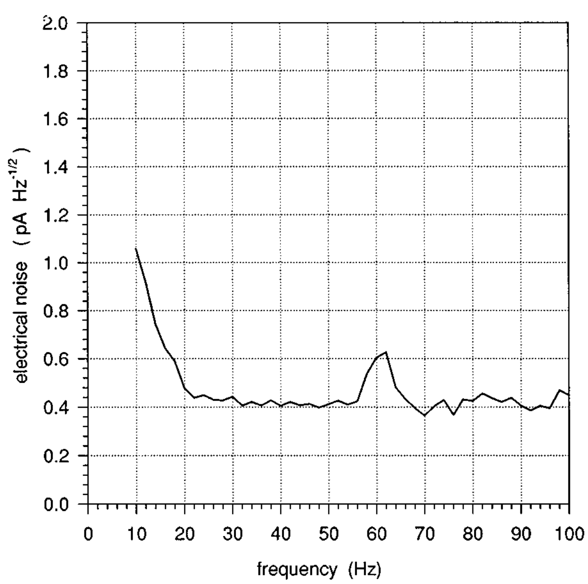

FIG. 4. Electrical noise as a function of frequency, measured by the current input channel of a lock-in amplifier under dark conditions.

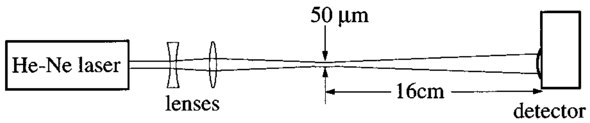

FIG. 5. Diagram of optical arrangement for measuring deflection of optical probe beam.

laser. The output power of the laser was equal to 2.0 mW. Through a pair of lenses, the beam was focused down to a $1/e^2$ waist diameter of 50 μm, and the detector was placed at a distance of 16 cm beyond the beam waist. The diameter of the beam at the plane of the detector was equal to 2.6 mm. This arrangement of optical components, shown in Fig. 5, duplicates typical conditions for an optical probe beam deflection experiment. Figure 6 displays the measured noise in units of electrical current, and also in equivalent units of angular deflection of the optical beam, using the beam waist as the location for the vertex of the angle. This sort of test can be useful for selecting a modulation frequency to provide maximum signal-to-noise ratio in a photothermal deflection experiment. Over the observed frequency domain, the measured deflection noise ranges from about 1 nrad/$\sqrt{\mathrm{Hz}}$ to greater than 20 nrad/$\sqrt{\mathrm{Hz}}$. Typical signal amplitudes encountered in photothermal deflection spectroscopy experiments may vary from less than[6] 10 nrad to greater than[10] 100 mrad. The features of the curve in Fig. 6 are particular to the optical apparatus used in this experiment, and may be caused by thermal and electrical fluctuations in the laser head, mechanical vibrations of optical components, and air currents. The electrical noise of the system with the addition of the probe beam is more than three orders of magnitude greater than that observed with dark conditions. Therefore, observed noise in this experimental configuration is dominated by actual pointing noise of the probe beam, rather than by electrical noise.

Finally, the power of the probe beam was reduced by means of an attenuating filter, down to a level of 1.4 μW,

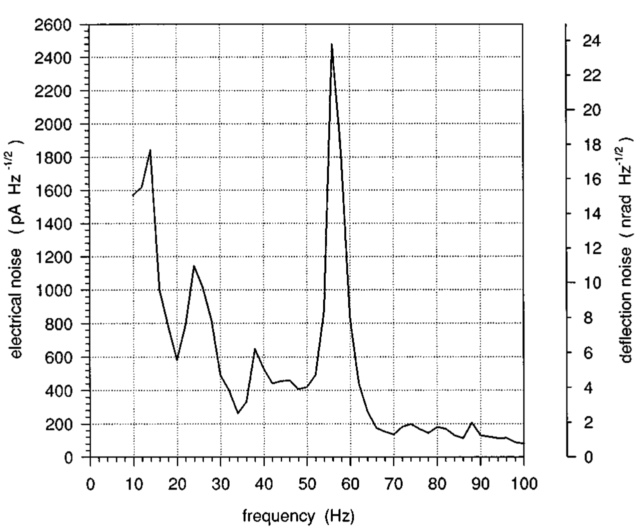

FIG. 6. Noise as a function of frequency for observation of a probe beam with 2.0 mW optical power.

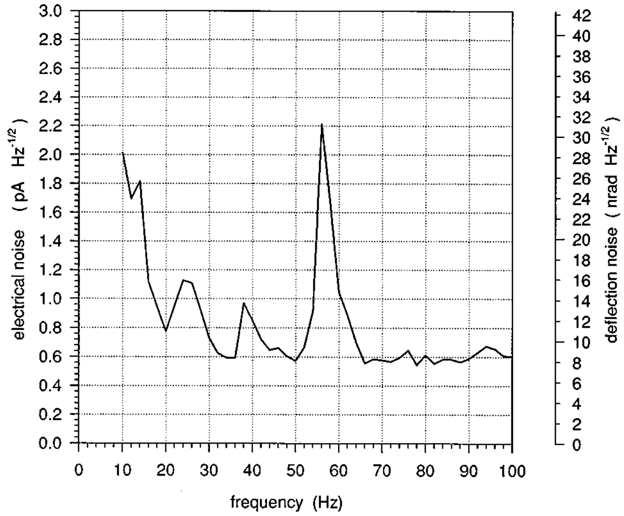

FIG. 7. Noise as a function of frequency for observation of a probe beam with 1.4 μW optical power.

and noise was measured as before. The results of this scan are shown in Fig. 7. Again, noise is reported both in electrical units and in angular units. Because the electrical response of the detector is proportional to the power of the probe beam, the conversion factor between the ordinate axes is different from that of the previous figure. At such a low optical power level, electrical noise becomes comparable to mechanical pointing noise. The shape of the curve shows the distinct features of both of the previous curves, Figs. 4 and 6. Electrical noise dominates for frequencies greater than 60 Hz.

IV. DISCUSSION

Like a conventional bicell, the discrete photodiode sensor is linear only for deflections that are small compared to the beam spot size. However, the two types of detectors fundamentally differ in their electrical configuration. With a conventional bicell, the sum of the amplified photocurrents from the separate channels provides an electrical measure of the total power of the optical probe beam. In the electrical configuration of Fig. 2, the discrete photodiode design nulls the photocurrents before amplification, so this measurement is not readily available. Therefore, if the power of the probe beam varies significantly during an experiment using a discrete photodiode detector, a separate reference measurement may be necessary to ensure accuracy of the deflection measurement. This reference measurement can be accomplished with an optical beam splitter (such as a microscope cover slide) to reflect a small fraction of the probe beam onto another photodetector. Alternatively, a measurement of beam power can be accomplished by modifying the basic electrical circuit of Fig. 2 so that the grounded end of one of the photodiodes is moved to the input of a second current amplifier instead.[11] However, in such a configuration, the input noise voltage generated by the second amplifier can appear as an additional source of current noise in the primary amplifier, via the terminal capacitance of the photodiode. The main benefits of the discrete photodiode design are its capability for effectively reducing thermal noise and its convenience in allowing a single amplifier to convert the nulled photocurrents into a voltage signal.

Another consequence of the discrete photodiode design is that, unlike the bicell, its electrical configuration does not permit a bias potential to be applied conveniently to the photodiodes. A bias potential is used for high frequency measurements, in which the photodiodes operate in the photoconductive, rather than photovoltaic, mode. However, because the optical gain provided by the lens in our design allows the size of each photodiode to be reduced, the terminal capacitance of the detector is decreased, thereby improving bandwidth limitations. The photodiodes used in this experiment are specified by the manufacturer to have a rise time of 0.4 μs when connected individually to an unbiased load of 1 kΩ, which is the impedance of the current input channel of the lock-in amplifier. Because the detector contains a pair of photodiodes connected in parallel, it would be expected that the rise time for the detector would be twice that of each photodiode, or 0.8 μs, corresponding to a -3 dB frequency bandwidth equal to 200 kHz. The current input channel of the lock-in amp has a specified bandwidth of only 70 kHz, so the amplifier limits speed for this particular experiment. Although this is more than fast enough for most optical probe beam deflection measurements, the bandwidth of our detector system could be increased further by using a different current preamplifier and by substituting faster photodiodes. In any case, noise at low frequencies is often a more important consideration than is response at high frequencies, and the detector design seems to be appropriate for such applications.

Initial tests have shown that the electrical noise obtainable with the detector system is orders of magnitude lower than the equivalent noise contributed by mechanical pointing instabilities of a probe beam in a typical deflection experiment. This suggests that efforts to correct for pointing noise may improve the performance of a beam deflection apparatus in which the discrete detector design is used. One corrective method[12] that has been used for photothermal beam deflection spectroscopy incorporates a 50% beam splitter to reflect half of the power of the probe beam onto a second position sensor. The amplified output of the second position sensor is electrically subtracted from that of the first, so pointing noise common to both sensors is canceled. A comparable system could be constructed with a pair of discrete photodiode position sensors, and the reduced electrical noise obtainable might enhance its effectiveness. With the discrete photodiode design, the second position sensor could be electrically connected in parallel to the first position sensor so that a single amplifier could be used for the pair of sensors.

Other methods of stabilizing the probe beam, such as spatial filtering or active feedback control, could also be used. Active feedback control systems[13,14] for laser beam pointing stabilization incorporate position sensitive detectors to monitor the position and angle of an input laser beam, amplifying the detector signals to drive mirror mounts with piezoelectric transducers. Because internal electrical noise may limit the ultimate performance of these systems, it might be of value to design a laser beam pointing stabilizer that incorporates discrete photodiode devices rather than conventional position sensitive detectors.

Deflection measurements in two dimensions could be accomplished with an optical beam splitter and two discrete photodiode detectors, each with an amplifier. Such a scheme would be comparable to commercially available quadrant detectors and to dual-axis lateral effect detectors, which require four op-amps to convert photocurrents to voltages, and additional circuitry to add and subtract the amplified signals appropriately. Although more mechanically cumbersome, a system using a pair of discrete photodiode detectors would be simpler to amplify electronically than a conventional two-dimensional position sensitive detector.

As electrical noise is reduced, it becomes possible to decrease the optical power of the probe beam without adversely affecting the performance of the system. A low noise detector might enable some deflection measurements to be performed on an optical beam that does not originate from a coherent laser source. Also, using a probe beam of low power is particularly desirable for certain measurements such as sensitive photothermal experiments[15] or other temperature controlled studies in which absorption of probe beam radiation by the sample can cause unwanted photothermal effects.

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